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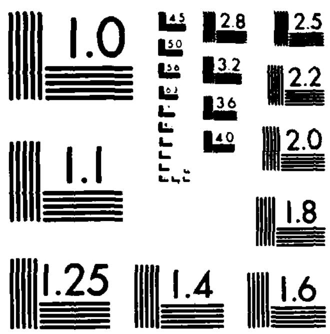
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Electrical Engineering Department

UNIVERSITY OF MARYLAND, COLLEGE PARK, MD 20742

Hg-ARC LAMP, PULSE EXCITATION

Final Report for ONR Contract

N00014-85-K-0541

Submitted by

U.Hochuli

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General Electric type B-H6 high pressure Hg-Arc Lamp, electrode-less, 13 mg Hg, CW 800 W 2.45 GHz excitation, spectrum, lifetest result. With electrodes, RF simmering, capacitor discharge pulsed, spectra, life test result, DC simmering, 200 MHz RF pulsed, spectrum, RF matching network.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Full power output over a period of 5000 hours was achieved with an electrode-less B-H6 type lamp with 800 W, CW, 2.45 GHz excitation. Devitrification became visible after 1500 h. Pulse excitation was achieved for simmering 2.45 GHz power levels of 500, 600 and 700 W by capacitor discharge producing 5 µs long pulses with peak currents of 200 and 400 A. Little sputtering appeared up to ~~10~~^{6} 200 A pulses at a rate of 10 pps. Stress cracks in the envelope seem to be the life limiting mechanisms for this type of pulsing. 200 MHz pulse excitation with 40 mA DC simmering and without forced air cooling was also achieved. The WWII radar transmitter used was unreliable and furnished only 40 KW pulses.

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Introduction

The development of a laser, from its invention to a practical and reliable device, is an extremely difficult, time-consuming task. From the thousands of lasing transitions found, there are roughly a dozen commercially viable lasers available on the market. Thus, it is not surprising that the Navy's requirements for a practical and viable blue-green laser still has not been met more than twenty years after the invention of the first laser. All the suitable candidates seem to have difficulties that are hard to overcome, from the short life of the corrosive Hg-Br laser, the lack of suitable diode arrays to excite the frequency-doubled Nd-Yag laser, to the missing crystal rod that could directly lase in the blue-green region of the spectrum. Work is being done in all of these areas including the latter one, and progress is very slow. There has been progress in the development of a suitable crystal, however, it still needs a good excitation source. It has been shown that the high pressure Hg-arc lamp can be excited to produce most of its output in the desired range around 3600 Å. However, the lifetime of these lamps is quite short, on the order of 50 hours for normal DC or 60 Hz AC operation.

We have speculated that one reason for this short life may be the gradual increase of the wall temperature as some of the sputtered electrode material renders the envelope less and less transparent. CW electrode-less excitation at 2.45 GHz has shown that this assumption appears to be correct. The result is a dramatic 100-fold increase of the tube life for RF excitation versus DC or 60 Hz excitation. This result is so promising that it makes sense to proceed with the desired pulse excitation.

Pulse Power Requirements

To reach the high plasma temperature for efficient output at 366 nm it is necessary to transfer a few joules of energy within a few micro-seconds into the pre-ionized plasma. Energy transfer with the usual capacitor discharge excita-

tion leads to electrode erosion and short life [1,2,3,4] of the DC pre-ionized lamp.

It is again tempting to try to solve the life problem with RF excitation. For this purpose it would be necessary to pre-ionize the lamp with 500 W of CW RF power and to superimpose 0.5 MW, 4 μs long, pulses. A maximum repetition rate of 300 pulses per second would lead to the average rated 1 KW input to the lamp.

RF Coupling

The coupling of RF power into an electrode-less plasma is not too difficult to achieve at low power levels where the plasma impedance is still large. At high power levels, it becomes an entirely different problem. Electric fields have to be limited to 10 KV/cm to avoid air breakdown. For fields of higher strength, the flash-lamp has to be immersed in a dielectric liquid that has low losses at RF and optical frequencies. The dielectric liquid must be chemically inert when exposed to a fair amount of UV radiation.

From the capacitor discharge excitation [1,2] it is known that a longitudinal electric field of the order of 500 V/cm is needed to drive a discharge current of several hundred Amps through the flash-lamp. The resulting electrical conductivity σ is nonlinear [5] and of the order of $10^4 (\Omega m)^{-1}$. This situation leads to a total flashlamp resistance of only a few Ohms at the current peak.

Since any RF frequencies of interest are much lower than the collision frequency, similar electrical conductivities have to be considered for RF excitation.

Wave propagation in the plasma is characterized by the propagation constant

$$\gamma = \alpha + j\beta = \sqrt{j\omega\mu(\sigma + j\ \omega\ \varepsilon)} \underset{\sigma \gg \omega\varepsilon}{\simeq} (1 + j)\sqrt{\omega\mu\sigma/2} \ ,$$

where $\frac{1}{\alpha} = \delta$ the skin depth, and the characteristic impedance

$$Z_0 = \gamma/(\sigma + j\omega\varepsilon) \simeq \gamma/\sigma = (1+j)\sqrt{\omega\mu/2\sigma} \ .$$

The field reflection coefficient Γ for a plane wave entering such a plasma is given by:

$$\Gamma = (Z_0 - \sqrt{\mu_0/\varepsilon_0})/(Z_0 + \sqrt{\mu_0/\varepsilon_0}) \approx - [1 - 2 Z_0/\sqrt{\mu_0/\varepsilon_0}]$$

$$|1+\Gamma| \approx 2|Z_0/\sqrt{\mu_0/\varepsilon_0}| = 2\sqrt{\omega\varepsilon/\sigma} .$$

Continuity of the tangential electric field components requires:

$$E_{11}^{i} + E_{11}^{r} = (1 + \Gamma) E_{11}^{i} = E_{11}^{t} \qquad \text{or}$$

$$|E_{11}^{t}|_{max} = |1 + \Gamma| |E_{11}^{i}|_{max}$$

$$= 2\sqrt{\omega\varepsilon/\sigma} |E_{11}^{i}|_{max} .$$

Continuity of the current leads to

$$|E_{\perp}^{t}| \approx 2|E_{\perp}^{i}| \omega\varepsilon/\sigma.$$

Calculating the quantities of interest at 140 MHz and 2.4 GHz for incident field components of 10^4 V/cm yields:

ν	$\delta = \sqrt{2/\omega\mu\sigma}$	$\omega\varepsilon/\sigma$	$\lvert E_{11}^{t}\rvert$	$\lvert E_{\perp}^{t}\rvert$
140 MHz	0.4 mm	10^{-6}	20 V/cm	10^{-2} V/cm
2.4 GHz	0.1 mm	$16\cdot10^{-6}$	80 V/cm	0.16 V/cm .

These values show that electrode-less RF excitation is not simple anymore for such low plasma impedances. It can be argued that an even higher RF frequency can increase $|E_{11}^{t}|$ at the expense of a still smaller skin-depth.

Series excitation with internal electrodes has its own problems as well. The input impedance can be considered the same as the one resulting from a lossy section of a shorted transmission line of the length of the flash-lamp. With the characteristic parameters:

$Z = r + j\omega L$, the series impedance per m,

$Y = j\omega C$, the admittance per m,

$Z_0 = \sqrt{Z/Y}$, the characteristic impedance,

$\gamma = \sqrt{Z\,Y}$, the propagation constant,

the input impedance calculates as:

$$Z_{in} = Z_0 \tanh \gamma\ell \approx Z_0\, \gamma\ell$$

$$= \sqrt{Z/Y}\sqrt{Z\,Y}\ \ell = Z\ell = r\ell + j\omega L\ell \ .$$

If the flash-lamp resistance is taken as

$$r\ell \approx 2\Omega, \text{ and } L = (\mu_0/2\pi)\ln(b/a) = (4\pi\cdot 10^{-7}/2\pi)\ln(37.5/1.5) = 6.4\cdot 10^{-7} \text{ H/m}$$

$$\omega L\ell = 2\pi\cdot 140\cdot 10^{6}\cdot 6\cdot 4\cdot 10^{-7}\cdot 3\cdot 10^{-2} \approx 17\Omega$$

the input impedance becomes:

$$Z_{in} = 2 + j\ 17\ \Omega \text{ at } 140 \text{ MHz.}$$

For a dissipation of 10^6 W, a peak load voltage of 17 KV is needed to drive a peak current of 1000 A through the lamp. The situtation is even worse because the electrode lead inductance further increases the necessary load voltage. Planar electrode connections would be ideal but are not very likely achievable. Electrode designs are severely limited by the very high pressure, up to 4500 PSI, that requires very strong seals between the quartz envelope and the electrode leads.

The damage mechanisms that have to be considered are electrode erosion at current densities in excess of 1000 A/sq cm and a very hot plasma close to the

quartz envelope. Insufficient knowledge of the processes in the boundary layers of the plasma prevent theoretical answers and necessitate experimental investigation.

Modes of Operation

There are basically four possible modes to provide pre-ionized pulse excitation of the electrodes in a high pressure Hg-arc lamps. These modes are:

1. DC pre-ionization, capacitor discharge pulse
2. RF pre-ionization, capacitor discharge pulse
3. DC pre-ionization, RF pulsed discharge
4. RF pre-ionization, RF pulsed discharge

We have proposed to look into methods 2 and 3 or 4.

RF Pre-ionization, Capacitor Discharge

Instrumentation

To work in this mode we have used pre-ionization power from a 5 KW Cober model 1827 2.45 GHz transmitter. A thyratron pulser was built to discharge a 1.6 μF capacitor through the residual inductance of the discharge circuit into the arc lamp. The thyratron is an old fashioned device but far more reliable in abusive experimental applications than a solid state switch. The 8613 hydrogen thyratron used has a rated maximum peak current of 500 A. For short periods of time it switched up to 800 A and performed flawlessly. A Pearson Electronics Model 110 current transformer and a Tektronix P 6015 high voltage probe were used to provide monitoring signals from the pulse current and voltage. The light output perpendicular to the lamp axis was observed in the center of the lamp with a 0.5 m Jarrell Ash model 80-020 spectrometer. The instrument, used with a 0.4 mm wide slit and a 1180 lines per mm grating, blazed at 3000 Å, has a resolution of 6.4 Å.

A 1P28 photomultiplier with cathode follower and a rise time of about 1 μs was used to monitor the specctrometer output. A variable high voltage supply was

used to vary the photomultiplier gain over a wide range. The wide gain range was necessary to compare the output spectrum of the lamp with 800 W CW excitation with the pulsed lamp spectrum.

Light Output

800 W RF CW Spectrum

Figure 1 shows the spectrum of our arc lamp for this type of excitation. Absolute values were calculated by using the General Electric data shown in Figure 2. We have not been able to duplicate the broad spectrum shown in Figure 1b [1]. The General Electric measurements also do not suggest that the lines are that broad.

All of the pulsed spectra were observed with the same optical neutral density filter and spectrometer settings by reducing the photomultiplier gain in known steps. Absolute spectral power densities were then calculated by using the CW spectrum as reference and under the assumption of an indentical angular distribution of the output spectra.

Pulsed Output

The spectrum for 200 A peak pulse current and 600 W RF pre-ionization is shown in Figure 3.

Spectra for 400 A peak pulse current and 500, 600 and 700 W RF pre-ionization levels are shown in Figures 4 to 6.

Light Pulse Duration

Our measurements indicate spectrally varying light pulse durations: up to 20 μs in the line centers and considerably shorter light pulses off line centers of about 10 μs. This observation agrees well [3] but is not consistent with the observations [1,2].

Typical pulse shapes of the electrical voltage and current with the corresponding light output are shown in Figure 7.

Experimental Lamp Life

a) 800 W CW RF excitation

Previous results indicated that the electrode-less lamp tested still yielded about half of the original power output at the 366 nm line after 5000 hours of continuous service. After 1500 hours devitrification started to appear in the center of the lamp and after 5000 hours a central, 1 cm wide, section of the lamp was quite white.

We realized that the apparent reduction in power output with constant input power could only be valid for a small part of the spectrum. Uniform spectral reduction of output power would increase the wall dissipation and result in melting of the quartz envelope. Further checks revealed that the lamp had performed even better. Comparison of the spectra of the old lamp and a new one indicated that they were alike within experimental errors of about 10%. The apparent power loss was later traced to malfunctioning measurement equipment.

Lamp life of 5000 hours for a 10% derated Hg-arc lamp of the B-H6 type is exceptional. An electrode-less 500 W lamp of this type, fed with a cheap microwave oven magnetron and power supply could make it an attractive light source. The electrode-less lamp is also cheaper to produce, far more rugged without the electrode seals, and contains only 13 mg of Hg.

b) Pulsed Lamp with Electrodes

A 300 W simmering level was found to be inadequate. 250,000 200 to 400 A pulses at 30 pps produced enough electrode sputtering to render the envelope quite dark and opaque.

When a 600 W simmering or pre-ionization power level was used the lamp operated in the bright regime. Lamp life improved considerably: after 10^6 200 A pulses at a rate of 10 pps little sputtering had taken place. From the aspect of sputtering the lamp should last considerably longer.

A few, quite small, surface cracks were also noticed on the inside, in the

center, of the lamps quartz envelope. With the lamp on the shelf for a few weeks many more cracks appeared and what looked at first only as a small flaw became a serious defect.

It should also be mentioned that for this test the Hg distribution between anode- and cathode end was equalized after every set of 250,000 pulses.

700 W RF simmering level spectral output data was recorded with 400 A pulses and in addition even 700 A pulses were used for short periods of time with one lamp. Other lamps exploded after workering only for one or two minutes with 10 pps 200 A pulses.

Lamp explosions not only destroy the lamp, the quartz sleeve, guiding the cooling air over the lamp, disintegrates as well. To prevent poisoning of the laboratory precautions lead to be taken so that the Hg spill was contained and could be cleaned up safely with a minimal effort.

Explosion Limit

From the previous experimental results it has to be concluded that a simmering level of 700 W brings the lamps too close to the explosion limit for 200 to 400 A, 5 μs long, pulses at 10 pps. The addition of such pulses, each carrying an energy between 1 to 2 Joules, increases the average lamp input from 700 to only 720 W in a lamp designed for 900 W input. The additional shock waves and stress created by the pulses cause the catastrophic failure of the lamp envelope.

The original General Electric bulletin lists 8 Joules as the explosion limit for a single pulse without any other biasing power. The same bulletin recommends that a lower limit of 4 Joules per pulse under repetitive pulsing be used, however, no repetition rate is specified.

Hg Migration

The standard H6 lamp has a drop of Hg at each end of the lamp. Its electrode tips protrude slightly out of the Hg surfaces, a condition used to

stabilize the 60 Hz arc. Electrodes for RF excitation can be shortened so that their tips are below the Hg surface. It can be argued that no electrode sputtering can take place as long as the electrodes are covered with Hg.

We have found, as expected, that the Hg does not stay in place. Hg migration takes place as a result of temperature gradients and unidirectional pulse current flow. In the experimental set-up cooling air entered at the cathode end and Hg usually migrated to this end.

No such problems occurred for the electrode-less CW RF discharge where just a minimum of 13 mg of Hg was present, only slightly more than necessary for the gaseous phase at full load conditions.

Experiments with new lamps that had electrodes and contained only 13 mg of Hg were not successful. The electrode seals of these lamps turned out to be more delicate and cracked easier, even under CW condition. It is also possible that the shock waves in the pulsed lamp are more vicious and damaging if very little liquid Hg is present.

Lamp Construction

A few years ago we were able to find an old batch of 30 General Electric B-H6 lamps under Maryland State Surplus. We bought these lamps and used them up for these experiments.

General Electric no longer manufacturers these lamps and the only remaining source is the Advanced Radiation Corporation. The company was quite helpful in providing new lamps with and without electrodes. We have used these lamps under quite different conditions than they were designed for. Under our adverse conditions and observing only a very limited number of these new lamps we found that the General Electric electrode seals were more stress resistant. The General Electric lamps had brass tube end sleeves, attached with Sauereisen cement. The tungsten electrodes had spot welded stranded wires attached which were soft soldered to the brass ends. The new lamps have sleeves attached with

fixture is excessive at 200 MHz. This reactance was over 100 Ohms with the lamp mounted across the large 2.45 GHz waveguide.

The lamp was finally used in a 1 5/8" terminating coaxial section following the tuner. Pre-ionization was applied to the lamp in the form of a 40 mA DC current supplied through a RF choke and the 57 pF feed through capacitor shown in Figure A in the appendix. This bias current was sufficient to bring the lamp up to operating temperature in the absence of forced air cooling.

The pulse spectrum of the lamp, measured in this set-up, and fed with 40 KW, 5 μs long, 200 MHz pulses at the rate of 60 pps is shown in Figure 8.

Proper life testing would have required forced air cooling, RF pre-ionization and a reliable pulse transmitter that can deliver the necessary power into the non-linear lamp impedance without the continuous arcing and breakdown problems we encountered.

Conclusions

We have shown that it is indeed electrode sputtering that limits the life of high pressure Hg-arc lamps of the H6 type to 50 hours or less under 60 Hz CW operating conditions. A 10% derated electrode-less, RF excited, lamp gave full output over a period of 5000 hours. After this period of time the envelope was white in the central, 1 cm long, region. This internal devitrification did not seem to reduce the light output as measured in the center of the lamp and perpendicular to its axis.

With 600 W CW RF pre-ionization and 200 A, 5 μs long, capacitor discharge pulses at a rate of 10 pps very little electrode sputtering occurred over 10^6 pulses. Hg migration is an annoying problem but stress induced cracks in the central region of the envelope seem to be the life limiting factor under this load. Lamps with only 13 mg of Hg do not have the migration problem. Instead we found that our lamps with low Hg content developed seal cracks long

before 10^6 pulses were reached.

The argument can be made that ordinary flashlamps are capable of delivering output up to 10^8 pulses with considerably higher input energies than 1 or 2 joules per pulse and show no stress cracks in their envelopes. The high pressure H6 type Hg-arc lamp works under quite different conditions: Its inner surface area is only 1.5 sq cm and the pre-ionization produces a continuous Hg background pressure of severan thousand PSI. Superposition of pulses on top of this pressure bias is a far more vicious process than pulse excitation of an ordinary flashlamp without such a bias. However, it should be borne in mind that these lamps can perform quite well when used conservatively within their limits. The problem is to find these limits for a given type of pulse excitation.

Lamp excitation with 40 KW, 5 μs long, 200 MHz pulses at the rate of 60 pps and 40 mA DC pre-ionization was achieved. The spectral output was measured but the WWII radar transmitter continuously arced and broke down frequently. No reasonable lamp life testing can be done under such conditions. RF pulse excitation of the lamp requires well designed conservative transmitting equipment that can deliver the required power into a non-linear load, which can at best be matched only during the pulse peaks, without arcing and other breakdown problems.

Considering that this effort lacked any funding for transmitter instrumentation, that there was no choice of operating frequency range and our extremely limited operating budget we obtained very promising results which require more funding to complete.

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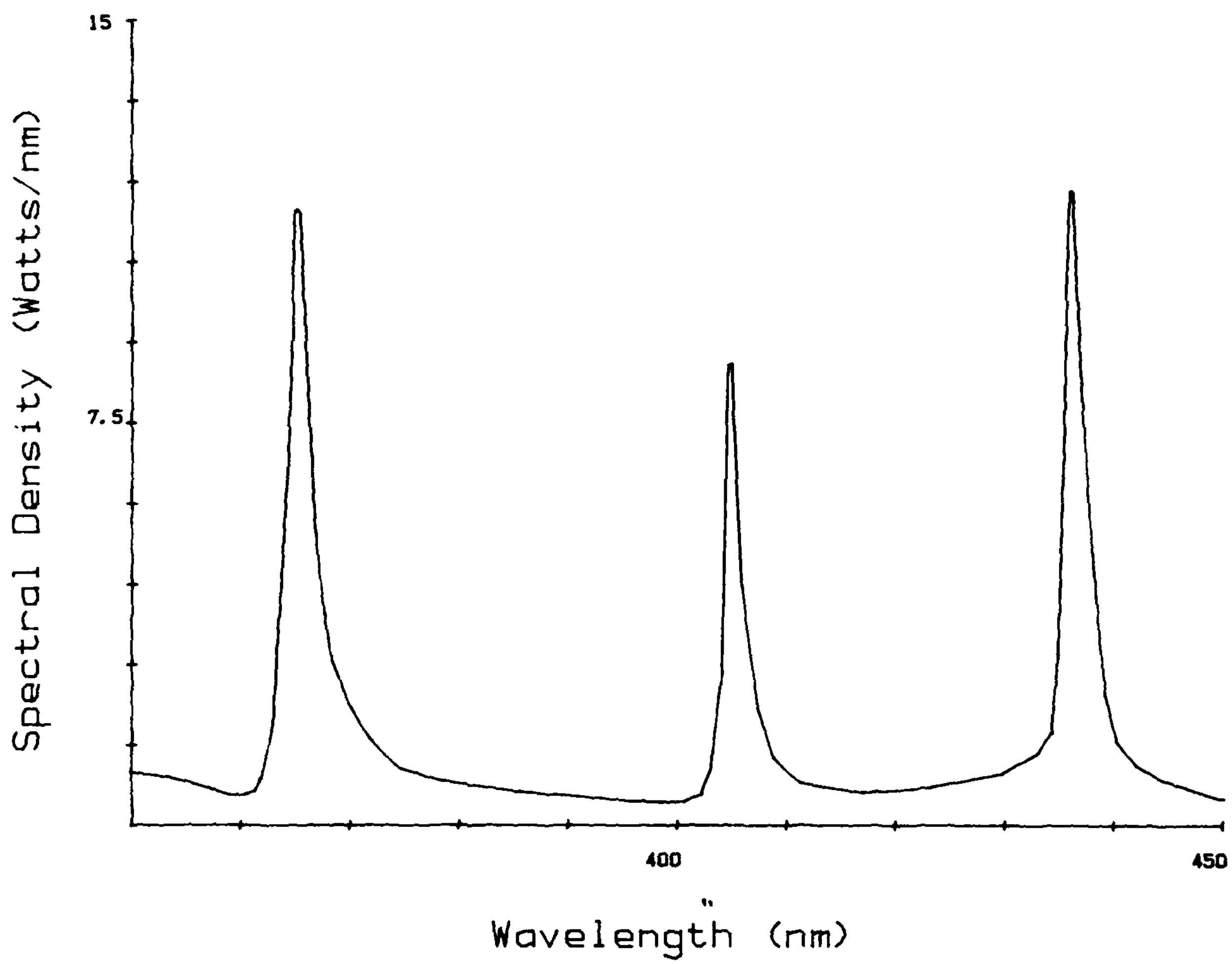


Fig. 1 Spectral Density vs. Wavelength
Electrode-less B-H6 lamp, 800 W CW at 2.45 GHz

A-H6 in No. 774 Pyrex Jacket

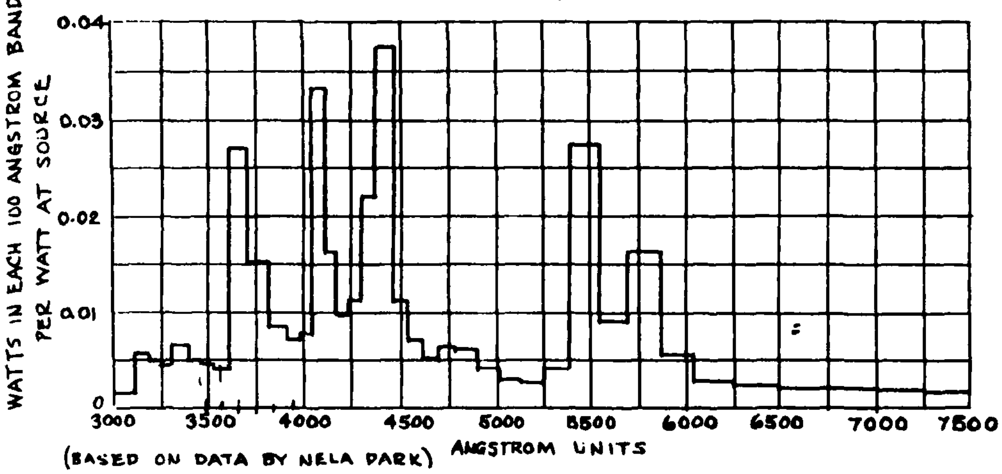


Fig. 2 Spectral Density vs. Wavelength given by General Electric

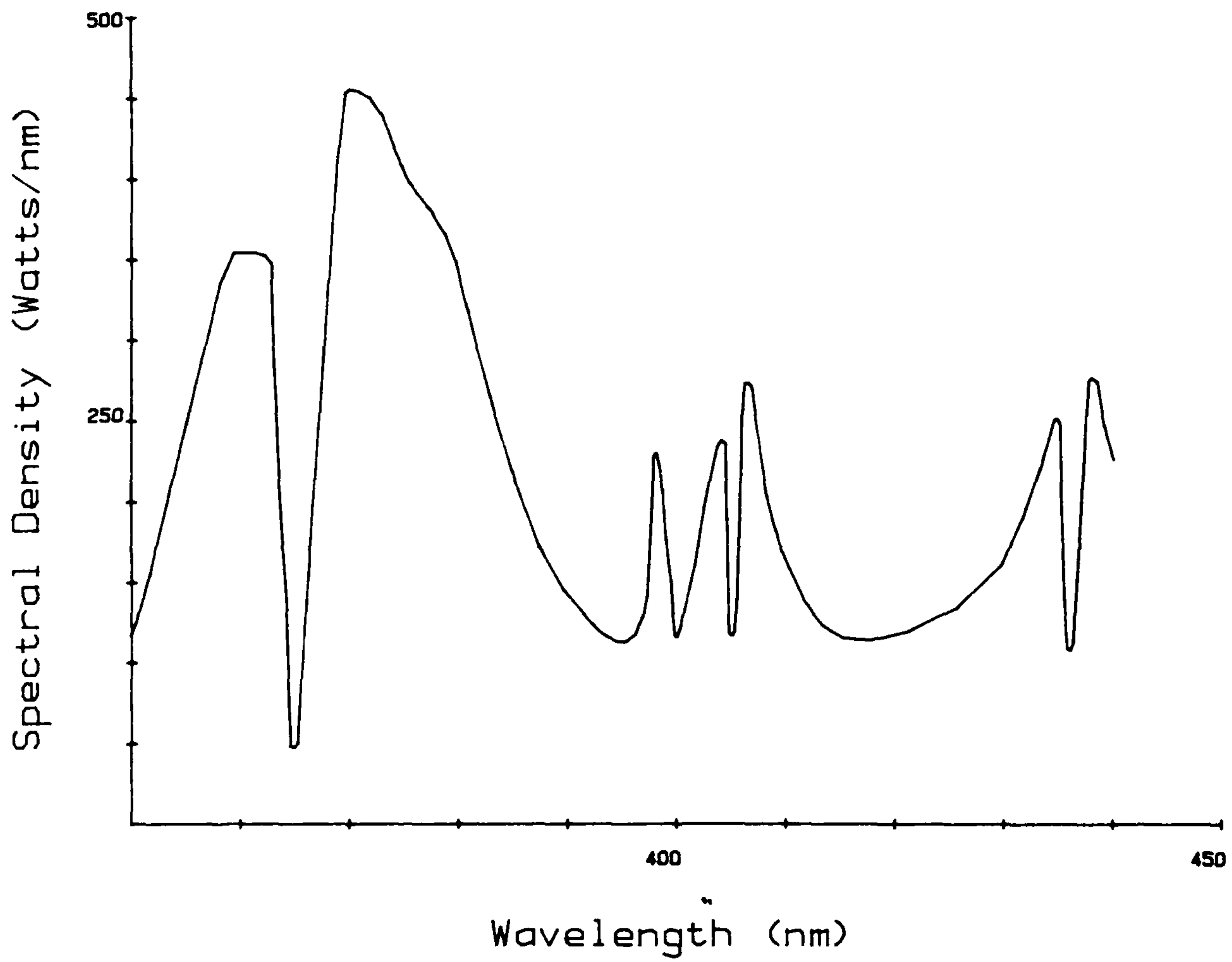


Fig. 3 Spectral Density vs. Wavelength
600 W pre-ionization at 2.45 GHz
200 A, 5 μs long capacitor discharge pulses at 10 pps
Stored energy: 1.6 μF charged to 950 V

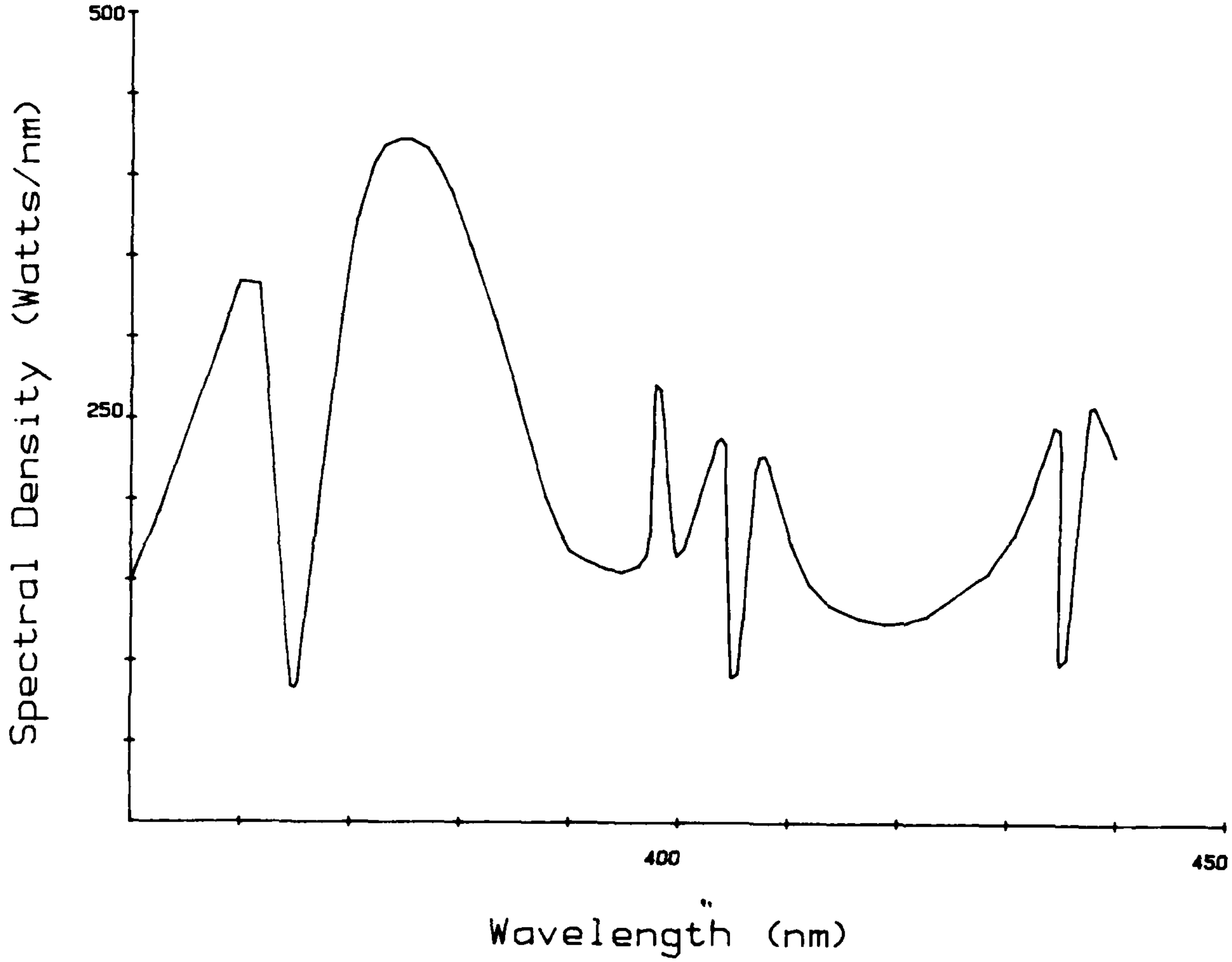


Fig. 4 Spectral Density vs. Wavelength
500 W pre-ionization at 2.45 GHz
400 A, 5 μs long capacitor discharge pulses at 10 pps
Stored energy: 1.6 μF charged to 1200 V

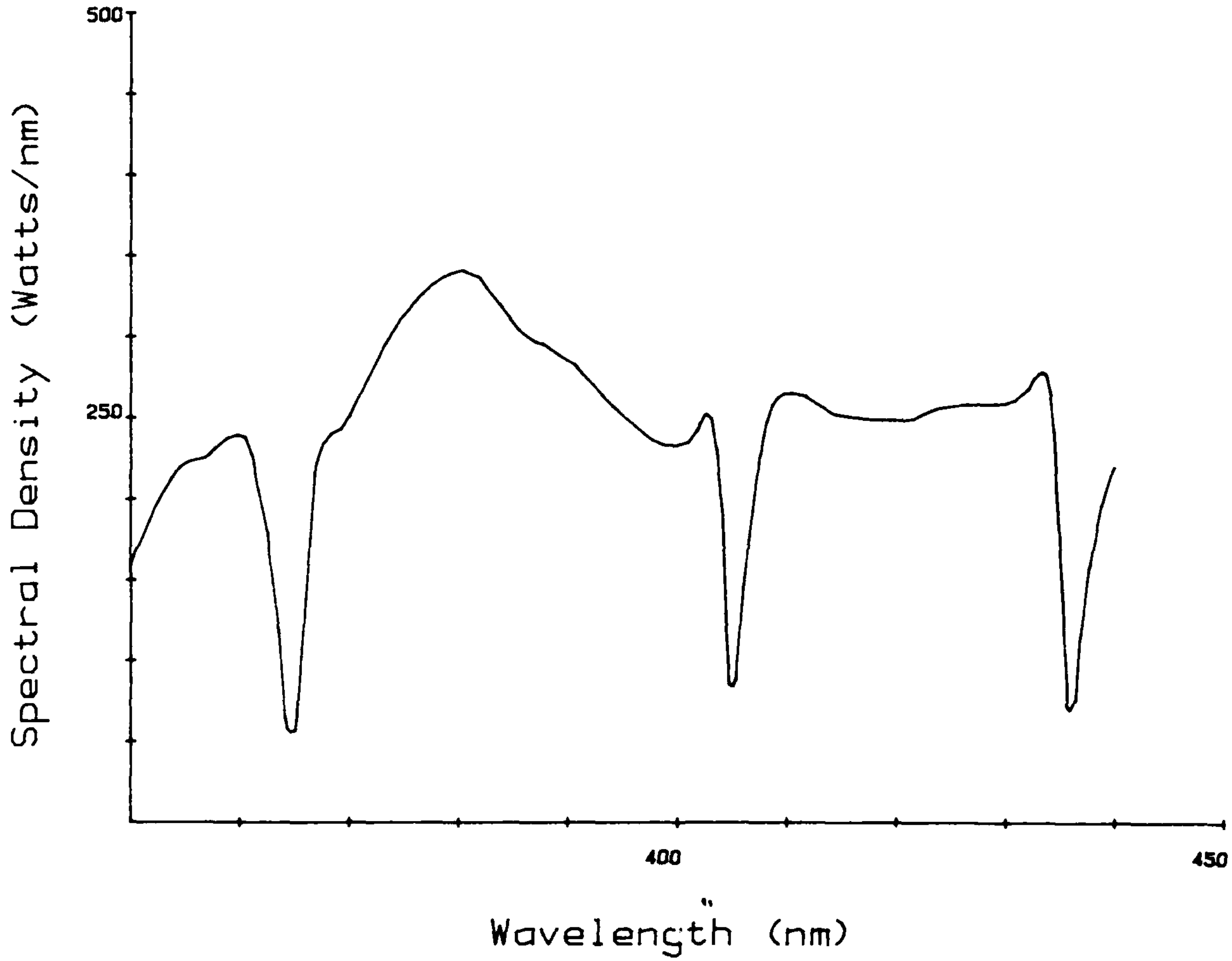


Fig. 5 Spectral Density vs. Wavelength
600 W pre-ionization at 2.45 GHz
400 A, 5 μs long capacitor discharge pulses at 10 pps
Stored energy: 1.6 μF charged to 1460 V

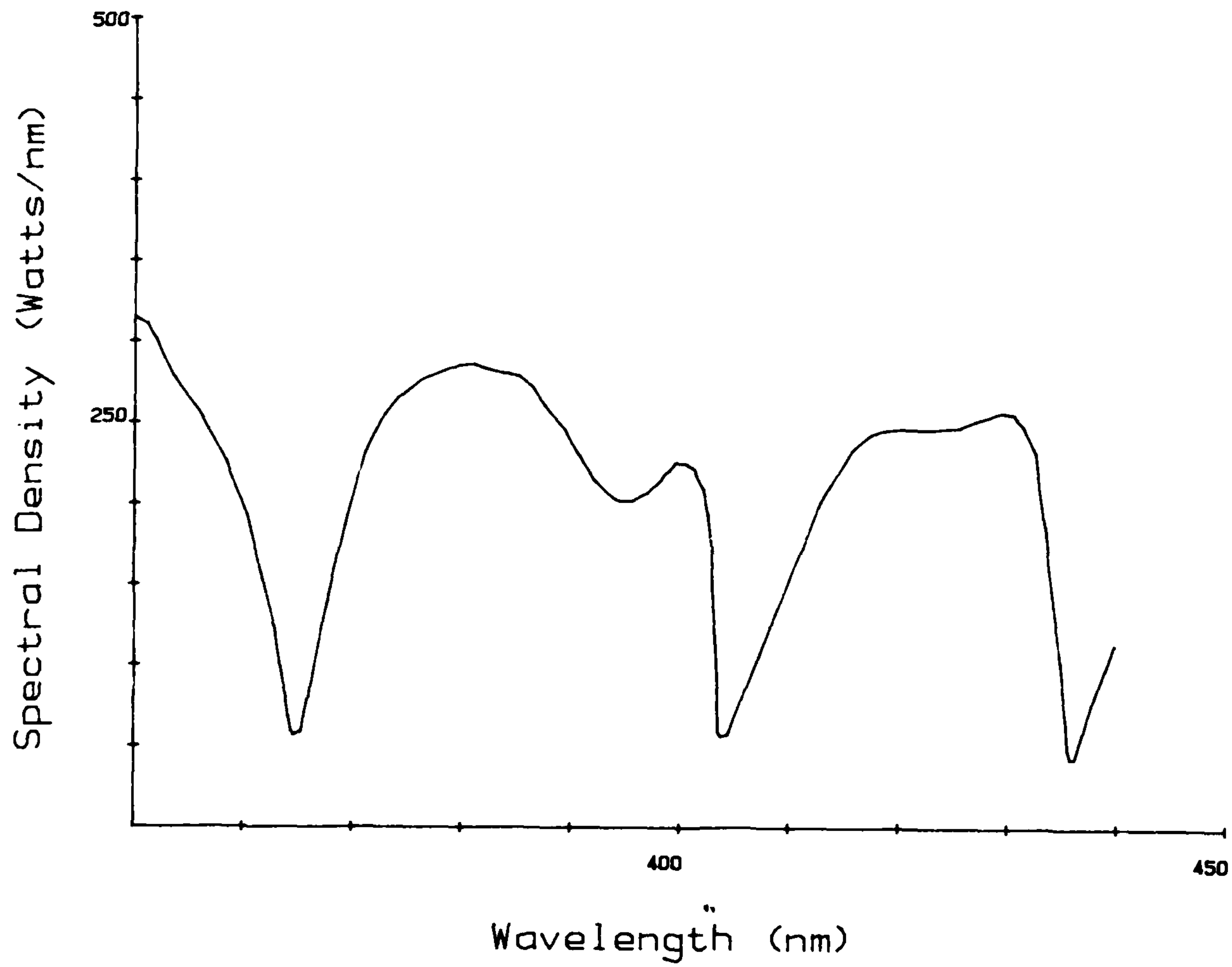
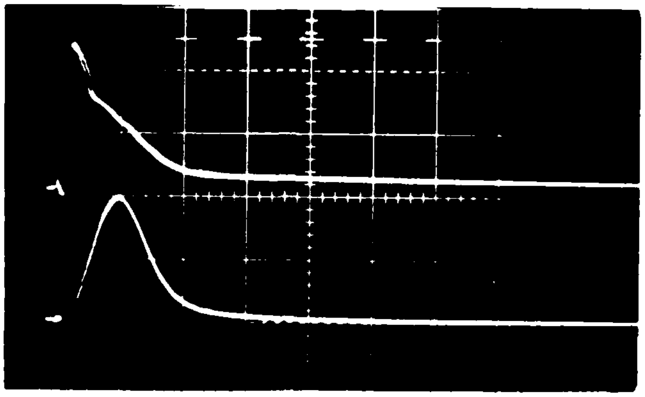
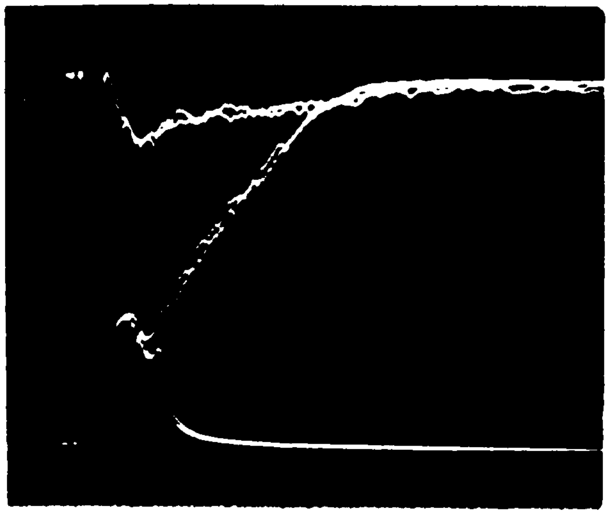


Fig. 6 Spectral Density vs. Wavelength
700 W pre-ionization at 2.45 GHz
400 A, 5 μs long capacitor discharge pulses at 10 pps
Stored energy: 1.6 μF charged to 1670 V



Sweep: 5 μs per div.
Top: Lamp voltage 500 V/div
Bottom: Lamp current 200 A/div
400 W 2.45 GHz pre-ionization



Sweep: 5 μs/div
Top: 366 nm line center
370 nm line wing — 1P28 output
Bottom: Lamp current 200 A/div
400 W 2.45 GHz pre-ionization

Fig. 7 Pulse shapes for Voltage, Current and Light Output

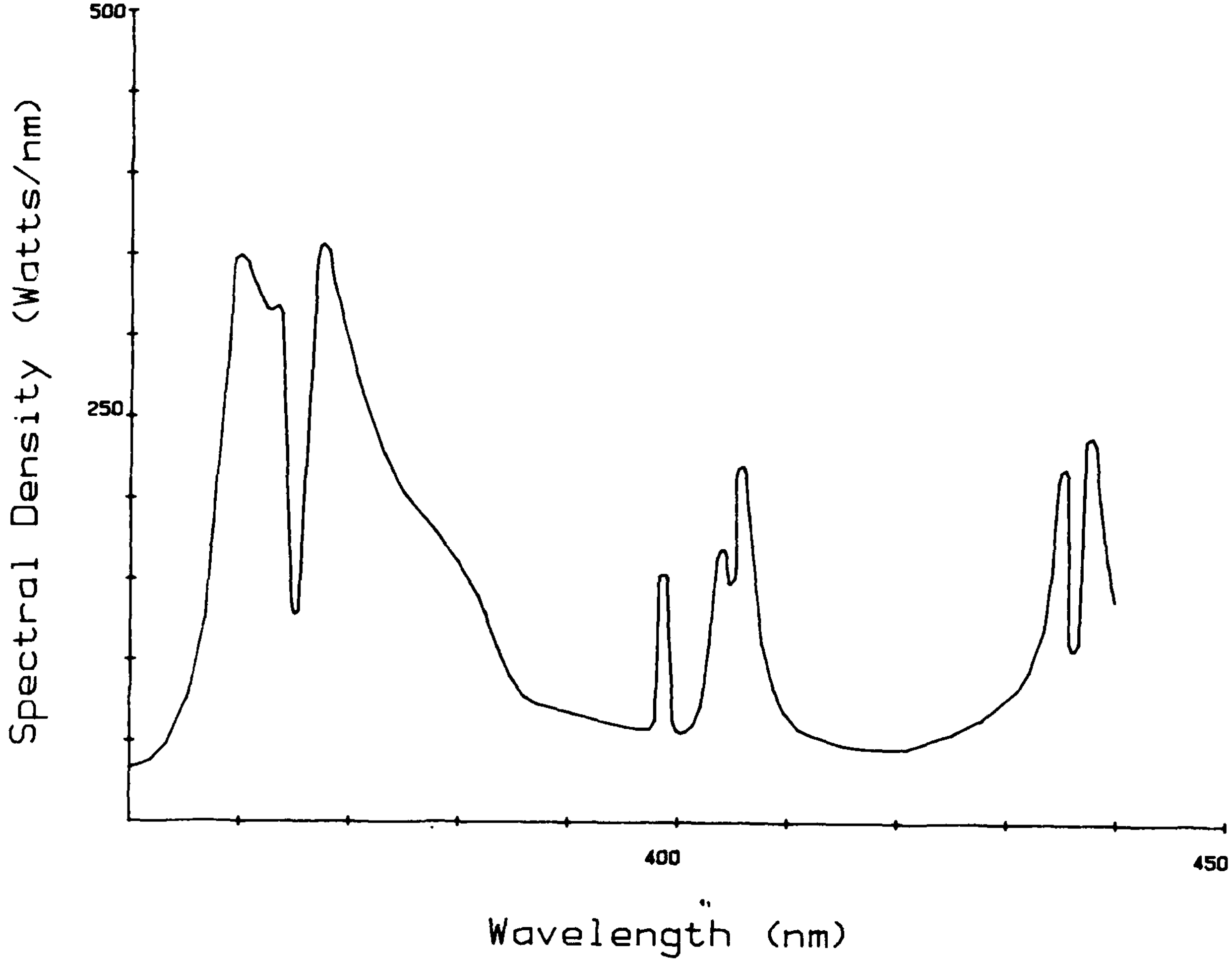


Fig. 8 Spectral Density vs. Wavelength
40 mA DC pre-ionization
40 KW, 5 μs long, 200 MHz RF pulses at 60 pps

Appendix

RF Matching

The resistive part of the load impedance decreases from a few hundred Ohms under simmering conditions to about 2 Ohms during the RF pulse. The reactive part of the load depends on the mounting of the lamp. If the lamp is part of the center conductor of the 1 5/8" coaxial system feeding it, its inductance per unit length can be calculated from

$$L/\ell = \frac{\mu_o}{2\pi} \ln \frac{R}{r} \quad .$$

Using this expression for a 3 cm long Hg column of 1.5 mm diameter yields an inductance of about $19 \cdot 10^{-9}$ H and a reactance of 26 Ohms at 212 MHz. The thin leads to the lamp increase its series reactance to about 52 Ohms.

The load impedance of $Z_\ell \simeq (2 + j52)$ Ohms has to be matched to the 50 Ohm transmitter output. To obtain results comparable with the 200 A capacitor discharge pulse requires an RF peak load current of 280 A. The load voltage produced by this current is on the order of 14 KV peak. A pulse power of 80 KW is required in the load to obtain the values quoted. It is obvious that the tuning network has to be carefully designed to handle these power levels.

The network designed and used is shown in Figure A. It consists of a 45 cm 1 5/8" coaxial main section with a 20 cm long movable dielectric Teflon slug. This section transforms the load impedance Z_ℓ to the output admittance Y = 0.02 + j B if the proper slug position x is selected. The parallel, 28.5 cm long stub with another dielectric, 5 cm long, Teflon slug furnishes the necessary capacitive susceptance $j\,B_s$ for matching:

$$Y_{res} = 0.02 + j\,B + j\,B_s = 0.02 \text{ mhO}.$$

Transmission line theory and transfer matrices were used to calculate the

curves shown. Figures A1 to A3 give the slug positions x and x_s for matching the given load impedance to the 50 Ohm transmitter output.

For $Z_\ell = (2 + j\ 52)\ \Omega$ and a 57 pF feed-through capacitor

$$Z_{\ell_{total}} = 2 + j\ 52 - j\ 13 = (2 + j\ 39)\,\Omega$$

has to be considered.

Figures A1 and A2 show that x=15 cm will transform $Z_\ell = (2 + j\ 39)\,\Omega$ into the normalized $Y' = 1 - j\ 8.5$.

Figure A3 yields the stub slug position $x_s = 6$ cm to produce $j\ B_s' = j\ 8.5$. Figures A4 to A7 indicate voltage ratioes at different positions in the tuner. Figure A4 shows that the peak load voltage of 280A·39Ω ≈ 11 KV transforms to 2730 V peak across the matched 50Ω line. Figure A7 indicates that the highest voltage occurs at the stub end and is about 7.6 times the line voltage or 21 KV peak. The resulting electric field at the inner 5/8" coaxial line conductor

is then $$E_r = \frac{V}{\ln(R/r)} \frac{1}{r} \simeq 30 \text{ KV peak per cm}.$$

This equals the breakdown strength of air and the stub has to be shortened or work in oil if power levels of 80 KW can be obtained from the transmitter. As mentioned before, the load is a nonlinear gas discharge and the values used in the calculations represent values approached once full load current is obtained. No calculations can be made during the transient turn-on time without knowledge of the load impedance as a function of current or time.

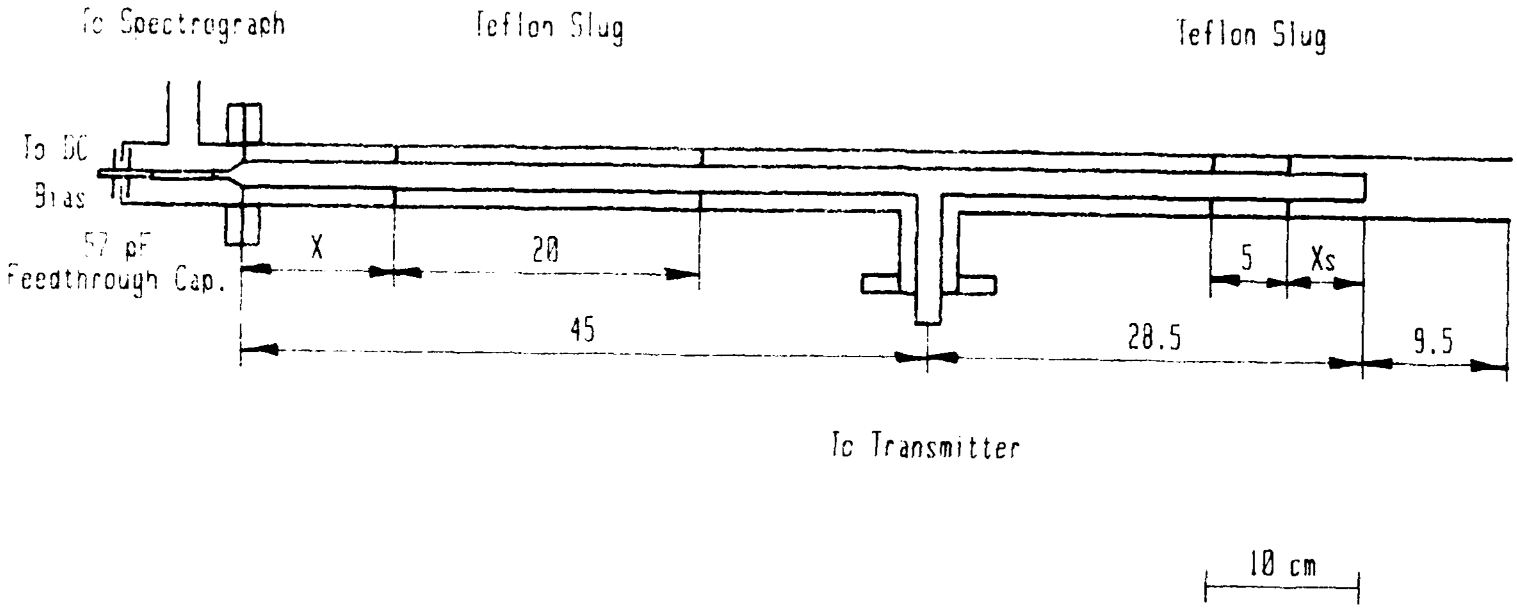


Fig.A , 1 5/8" Coaxial Dielectric Slug Tuner

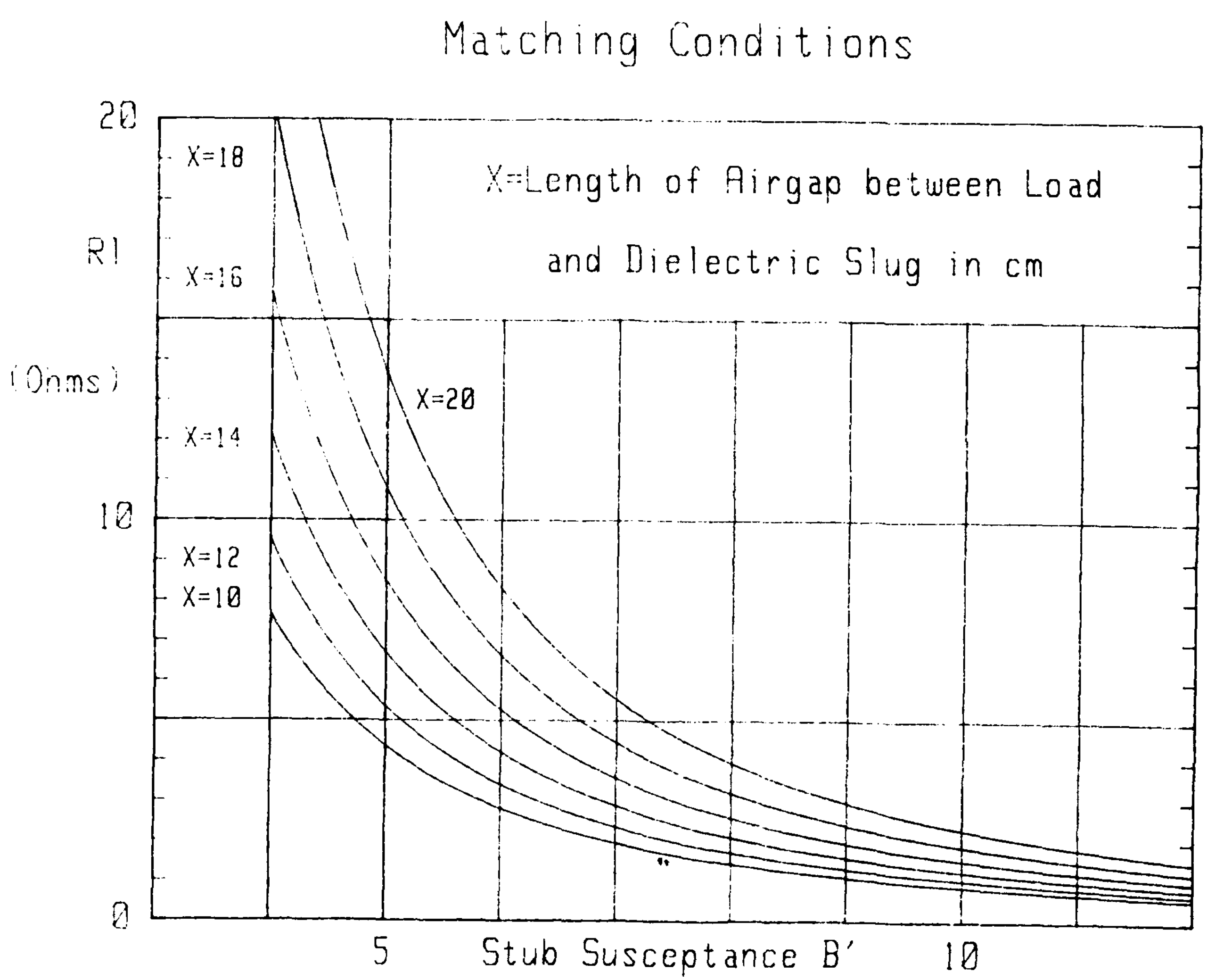


FIG. A1 , Load Resistance vs Stub Susceptance

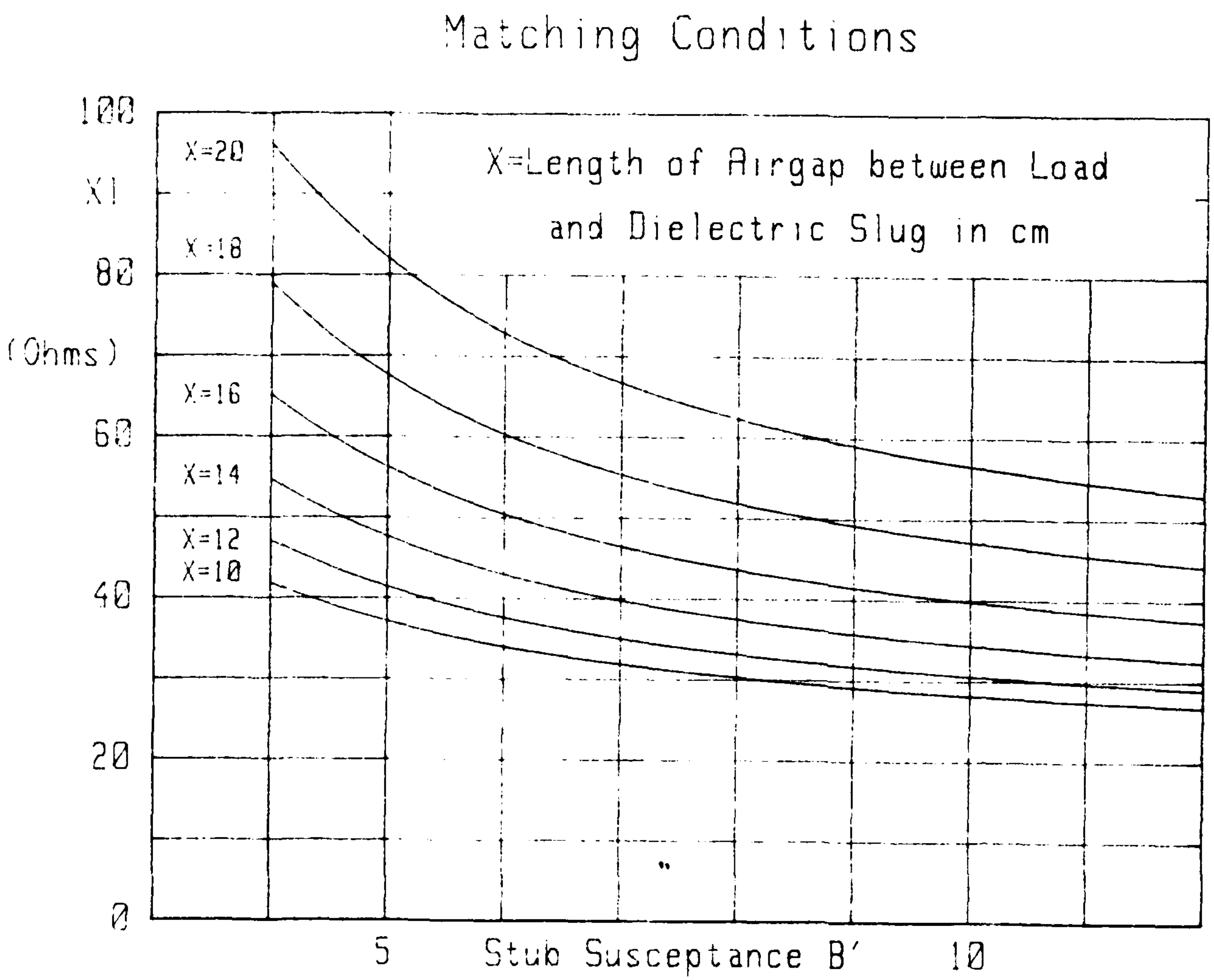


FIG. A2 , Inductive Load Reactance vs Stub Susceptance

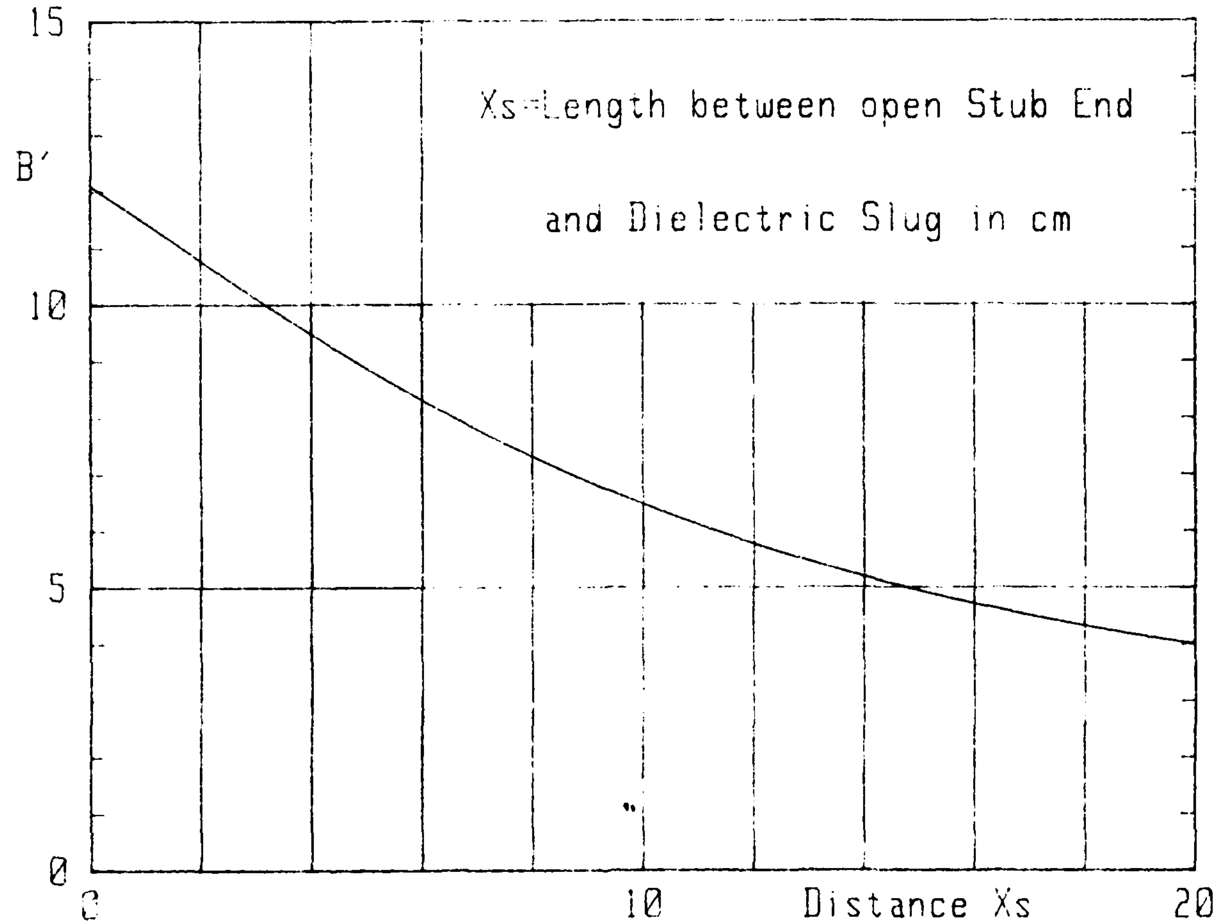


FIG. A3 , Normalized Susceptance B′ vs Xs

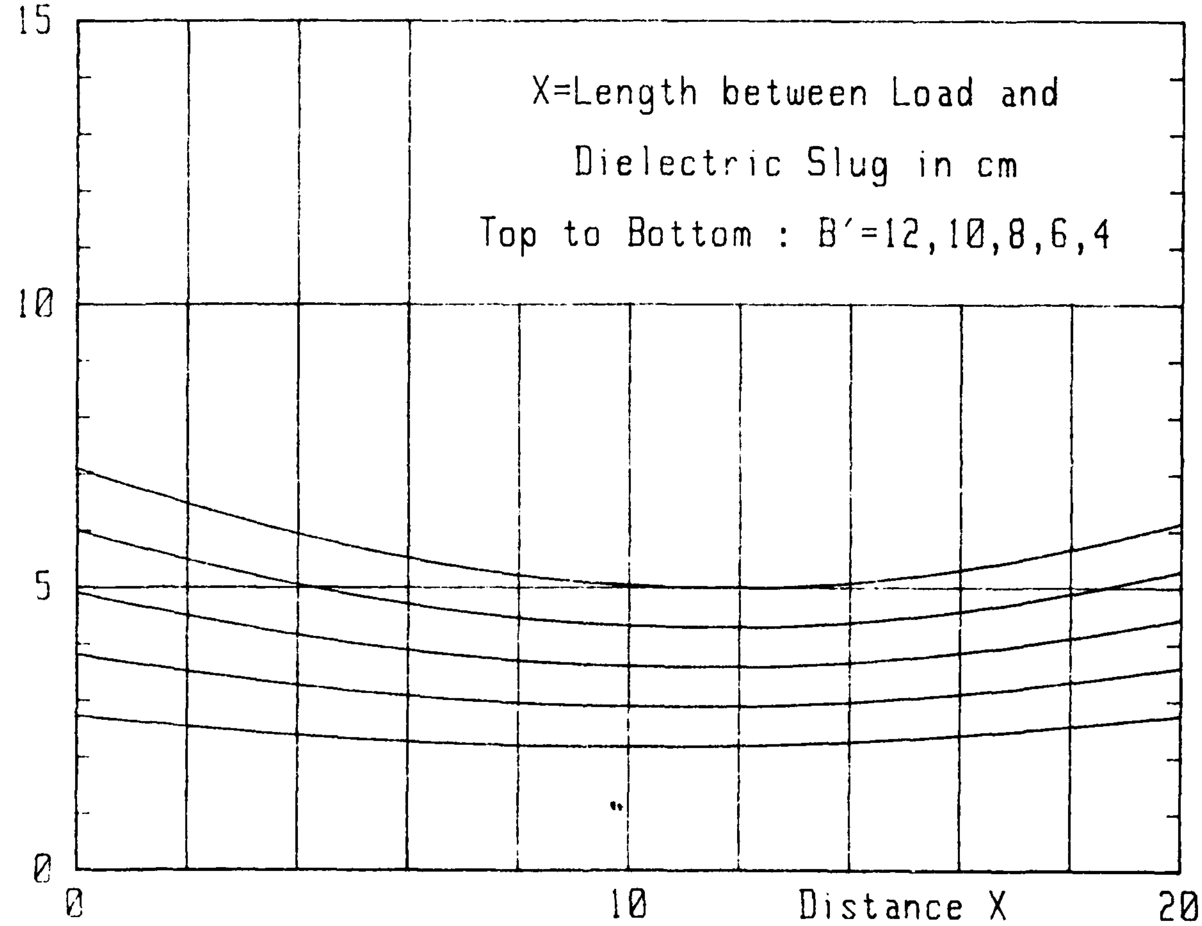


FIG. A4 , Normalized Line Voltage $|V(X+20)/V(45)|$ vs X

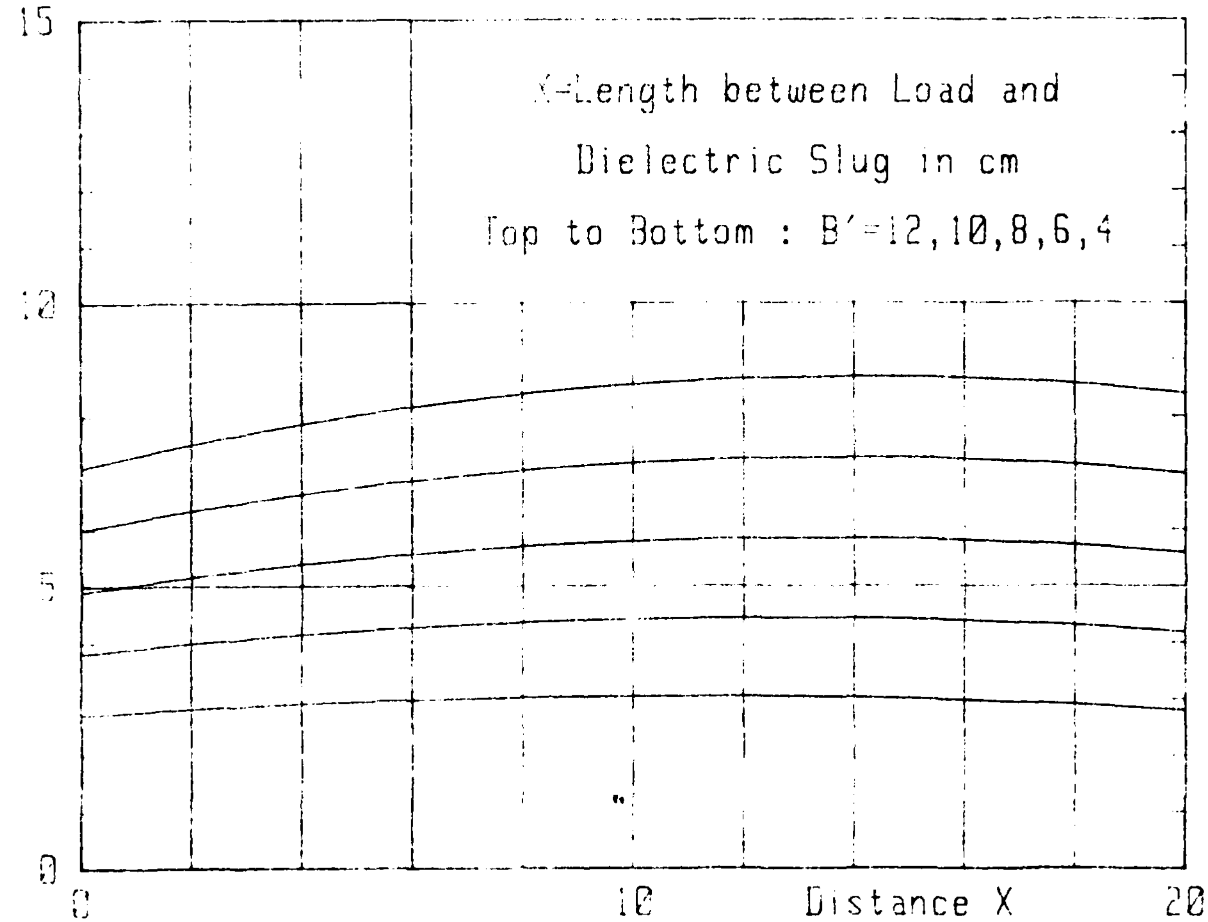


FIG. A5 , Normalized Line Voltage $|V(x+20)/V(45)|$ vs X

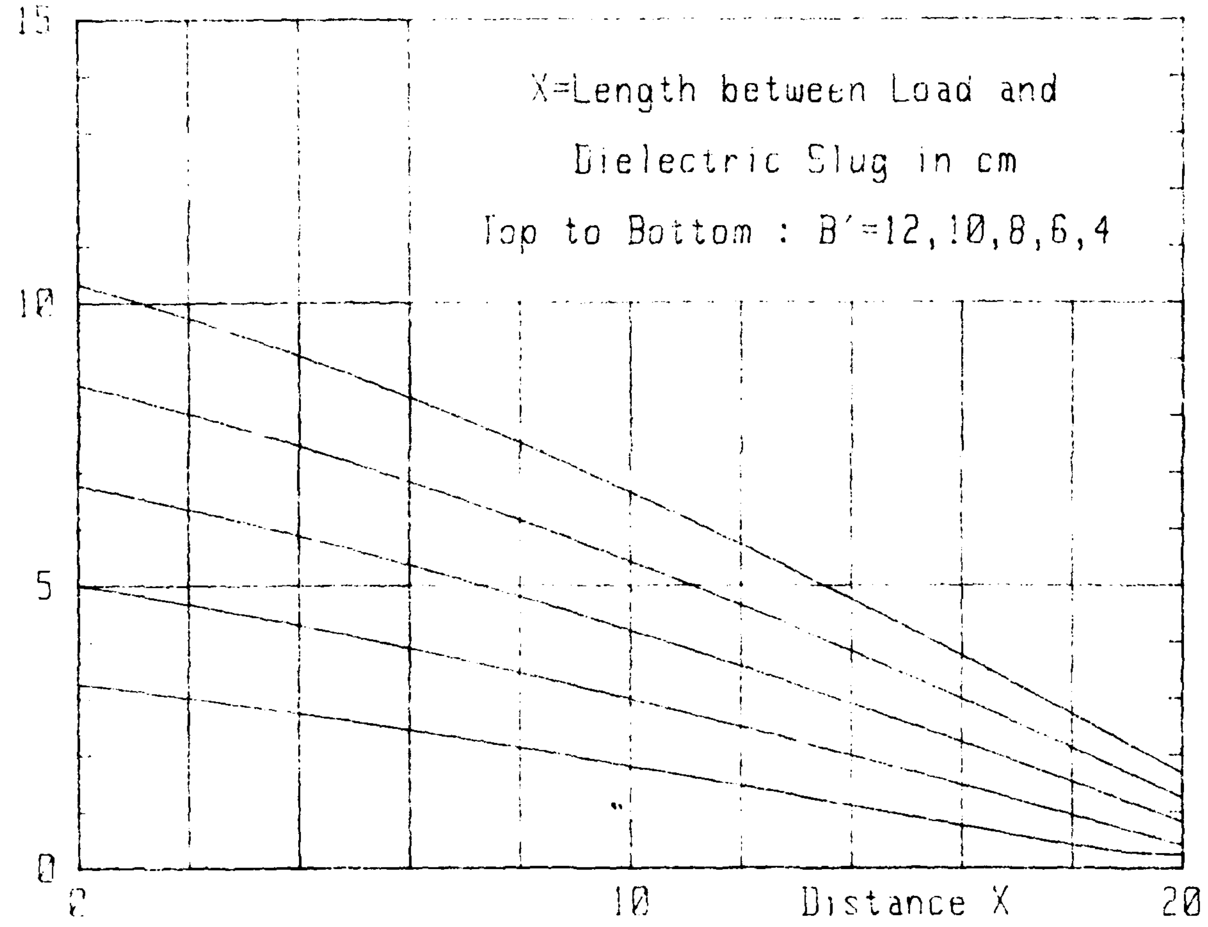


FIG. AG , Normalized Line Voltage $|V(X+20)/V(45)|$ vs X

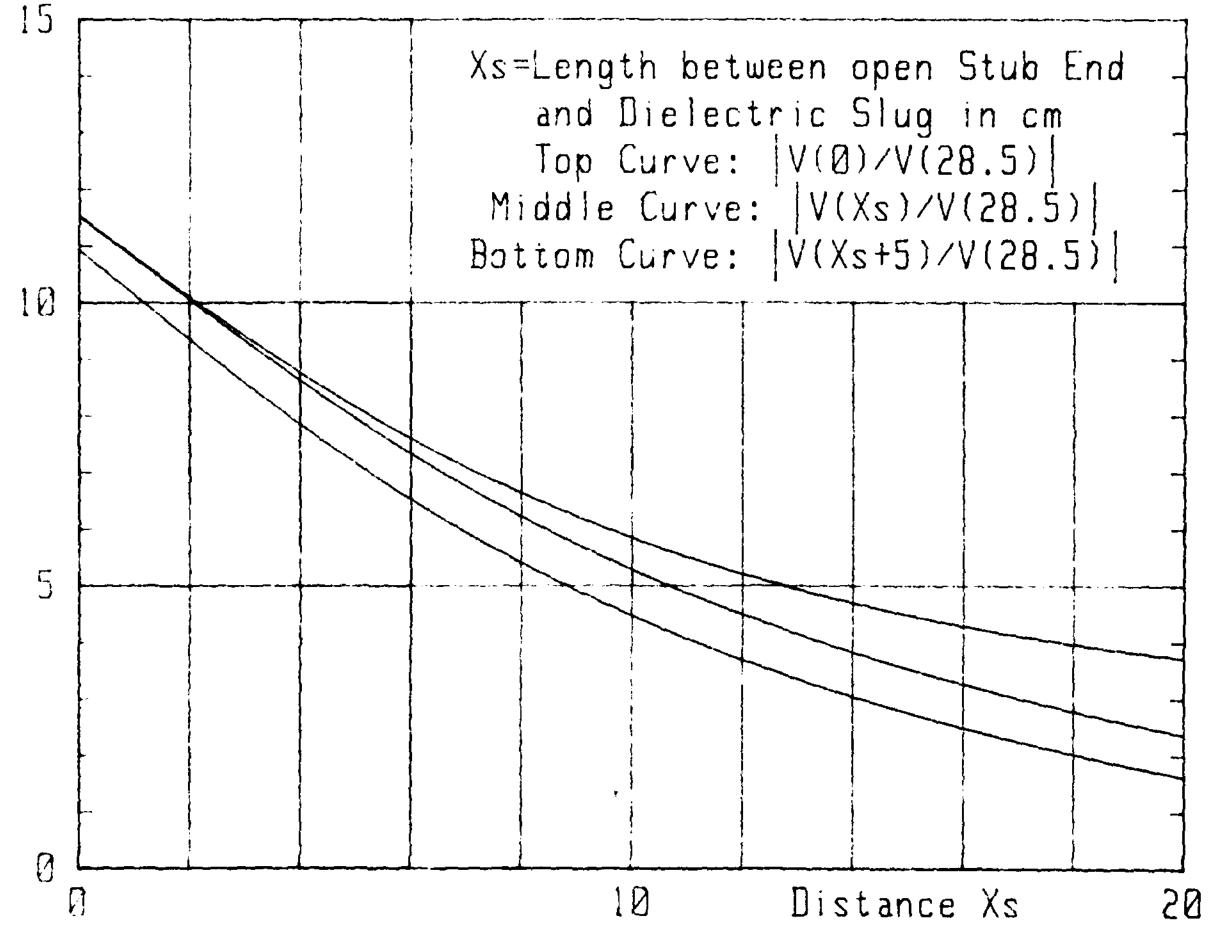


FIG. A7 , Normalized Stub Voltages vs Xs

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